Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

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T. LIFE OF THE RESERVOIR

By H. E. Thomas, H. R. Gould, and W. B. Langbein

In the preceding chapter, H. R. Gould has described the conditions that would mark the last stages of Lake Mead as a water-storage facility, and has indicated for certain assumed conditions the tonnage of sediment that would be accumulated in the reservoir area at that time. He has also discussed conditions at the time when the sediment accumulation would amount to about half the sediment-storage capacity and has pointed out that the usefulness of the reservoir will probably not be seriously impaired until that halfway point is reached. The calculated quantity of sediment—about 75 billion tons when the reservoir becomes completely filled, or 3,700 million tons at that halfway point—are essential items in the computation of the life of the reservoir.

The life, or the half-life, of the reservoir in years depends also upon the average annual rate of sediment accumulation. In the following sections the life of the reservoir is forecast first on the assumption that the average rate of accumulation in the 14-year period 1935-48 will continue in the future, and then on the basis of analyses of other hydrologic data for the purpose of evaluating the "normal" rate of accumulation.

PROJECTION OF OBSERVED RATES OF SEDIMENT ACCUMULATION

Some estimates of the probable life of Lake Mead have been based on projection of the observed rates of sediment accumulation at Hoover Dam. As shown by figure 24, the top of the sediment rose 100 feet in the first 3 years of operation of the dam, and then it rose another 40 feet by the fall of 1941, less than 7 years after water was first impounded. This rapid rise of the sediment level—to a position about halfway between the original river bed and the lower gates at the intake towers—could lead to very pessimistic estimates as to the life of the reservoir. However, the rapid rise is explained by the shape of the reservoir; the volume in the lowest 100-foot layer of the reservoir (below elevation 720 feet) constitutes less than 0.5 percent of the reservoir capacity, as shown by the original capacities in table 7. Records since 1941, too, show that sediment compaction is a very important factor at the dam, for by January 1950 the sediment surface at the intake towers was 38 feet lower than the maximum in 1941. Projections of the observed rate of sediment accumulation into the future necessarily lead to erroneous estimates of the life of the reservoir, if they neglect the factor of compaction.

Other estimates of the life of Lake Mead have been based upon projection of the ratio of sediment volume to the water-storage capacity of the reservoir. This was essentially the basis for the estimate made by Stevens (1946), for he assumed that practically all the sediments carried by the inflowing streams would be deposited in the reservoir below an elevation of 1,205 feet, and he assumed an average specific weight of 65 pounds per cubic foot for the accumulated sediment, which is about the average for existing deposits as determined in the 1948-49 survey. By evaluation of the data collected prior to October 1942, Stevens deduced that the sediment would accumulate at an average annual rate of 198,000 acre-feet, and that the reservoir would therefore be completely filled with sediment in 144 years. But in the 1948-49 survey it was determined that the volume occupied by sediment was 1,426,000 acre-feet, and thus the average annual rate of accumulation in the 14-year period was 102,000 acre-feet. By projection of this rate of accumulation, the time required for deposition of a volume of sediment equivalent to the original water-storage capacity of Lake Mead would be 280 years.

However, the maximum life of the reservoir will be considerably greater than this, because (1) the sediment-storage capacity is greater than the water-storage capacity of the lake and (2) the current average specific weight of the sediment will be increased by compaction. From consideration of the principles of stream gradation and the history of delta building in Lake Mead to date, Gould concludes (p. 217) that the sediment-storage capacity of the reservoir may be as much as 25 percent greater than the water-storage capacity. From analysis of core samples and other data, he estimates that the average specific weight of the sediment when the reservoir is completely filled will be 50 percent greater than the average of the
deposit in 1948. The 2,000 million tons of sediment deposited in the 14-year period (1935-48) constitutes only 2.7 percent of the calculated ultimate storage capacity of nearly 75,000 million tons. By projection of this rate of accumulation, the probable maximum life of the reservoir is computed to be about 520 years. The time required to reach the halfway point, when accumulation of 37,000 million tons of sediment will have reduced the water-storage capacity at permanent spillway crest to 13 million acre-feet, will be about 260 years.

"NORMAL" RATE OF SEDIMENT ACCUMULATION

In using the record for a 14-year period to forecast events 5 centuries in the future, we are using an exceedingly short base and projecting it for nearly 40 times its length. Any inaccuracies in that base are correspondingly magnified in the forecasts. Thus, if on the average it takes only 12 years for streams to carry additional quantities of 2,000 million tons, such as reached Lake Mead in the 14-year period of record, the probable life of the reservoir would be shortened by 75 years. The records at Grand Canyon show that there is sufficient variability in sediment load to justify a great range in forecasts as to the probable life of the reservoir. In the single year 1927 the suspended load of 480 million tons was equivalent to nearly one-fourth of the total carried in the 14-year base period; and in the 8 years 1926-33 the river carried 2,000 million tons of sediment past the Grand Canyon station—as much as was carried in the 14-year period 1935-48.

Hydrologists are generally agreed that the period 1935-48 was not a "normal" period, for the average runoff was appreciably less than averages for longer terms, and the sediment load also was less than the average for the entire period of record. The problem is complicated by the fact that the sediment-runoff relation since 1941 has been notably different from that recorded in earlier years (p. 104).

The following sections are devoted to an analysis of (1) existing records, to determine whether some of the variation in results may stem from changes in methods of collection of basic data; (2) observed variations in runoff and sediment load, and the modifications that may result from additional water-development projects upstream from Hoover Dam; (3) the effects of allowing some sediment to flow out of the reservoir; and (4) other factors that may produce minor changes in reservoir volume and thus may shorten or lengthen the time required for filling.

In analyzing the available data, one is frequently handicapped by a paucity or complete lack of information on certain important problems, and he finds himself forced to speculate to an extent that is not condoned in most scientific work. However, the purpose of this speculation is to qualify and limit the major speculation as to the probable life of the reservoir, and to indicate the fields in which our knowledge must be increased before the economic life of Lake Mead, or indeed of large reservoirs in general, can be evaluated accurately.

EVALUATION OF EXISTING RECORDS

The volumetric survey of 1948 provides only one point of correlation between runoff and sediment: 2 billion tons of sediment was carried into the reservoir by 176 million acre-feet of Colorado River water, plus the unmeasured flow of other tributaries. Any detailed analysis of the rate of sediment transportation in relation to stream discharge depends on records of suspended load, especially the record for the Colorado River at Grand Canyon.

GAGING OF SUSPENDED SEDIMENT AT GRAND CANYON

The sharp change in the annual sediment runoff relation at Grand Canyon since 1941 (fig. 22) may lead the curious minded to wonder whether changes in equipment or techniques used in the measurements might be partly responsible. In the past 25 years there has been progress toward greater accuracy in the measurement of suspended load in streams; the corollary to that statement must be that records for earlier years may be subject to greater error than current records.

Records of suspended sediment at Grand Canyon for the years prior to 1944 are based upon samples collected with the Colorado River sampler. The sampler was essentially a bracket, suspended from a cable, which held a pint bottle and, beneath it, a 50-pound elliptical weight. The bottle was held vertically, except of course for the angle of downstream drift, and the sample was admitted through a \( \frac{3}{16} \)-inch or \( \frac{5}{16} \)-inch orifice in the cap, sometimes with air exhaust. Sampling could extend downward as far as 1.5 feet above the stream bed, a limit set by the height of the bottle and the underslung weight.

Since April 1944 the D-43 depth-integrating sampler has been used at Grand Canyon. This sampler has a cast-bronze streamlined body with integral horizontal and vertical tail vanes; it weighs about 50 pounds. The bottle is inclined slightly from horizontal, and is filled from a \( \frac{1}{4} \)-, \( \frac{3}{16} \)-, or \( \frac{1}{4} \)-inch nozzle, selected according to discharge conditions at the time of sampling. Sampling extends downward as far as 0.3 foot above the riverbed.

A few field tests have indicated that the Colorado River sampler is erratic in comparison with the D-43
pliter.

In five comparisons at Grand Canyon, at depths ranging from 19 to 29 feet the Colorado River sampler on round-trip integration indicated concentrations ranging from 99 to 103 percent of those shown by a D-43 sampler.\(^\text{20}\) Sketchy comparative tests at other places in the Colorado River Basin (Benedict, 1944) are quite inadequate for correlation of records obtained by the respective samplers; but, as such as they are, they indicate that the Colorado River sampler registers less sediment than the D-43 sampler, especially in smaller and presumably shallower streams. In seven samples from streams discharging more than 10,000 cfs, the two samplers agreed within 2 to 12 percent, but in streams of lesser discharge the Colorado River sampler recorded 25 to 50 percent less sediment than the D-43. This under-registering may result in part from the inability of the Colorado River sampler to get down close to the streambed, where the coarser particles are concentrated.

These few tests give no indication that the sediment measured by the Colorado River sampler—that is, the recorded load prior to 1944—is excessive. If anything, the errors of this sampler would be in the other direction, so that the recorded load would be less than the actual. The change in sampling equipment cannot be held responsible for the generally lower concentration of sediment since 1942.

The method of computation of sediment concentration during the early years of record caused a slight exaggeration of suspended load during the period prior to March 1930. The computations were based upon the assumption that the sample would have a weight equivalent to that of an equal volume of pure water. As a result the calculated sediment load would be 3 percent greater than actual for a 5-percent concentration, and 6 percent greater for a 10-percent concentration. Sediment concentrations in excess of 5 percent were common in 1927 and 1929, and correction of these errors would reduce the very high recorded sediment loads in those years (Daines, 1949). However, the errors occur only in records for years prior to the beginning of construction of Hoover Dam.

UNGAGED INCREMENTS OF SEDIMENT

Only a part, albeit a predominant part, of the sediment entering Lake Mead is measured at Grand Canyon. The gaging station on the Virgin River at Littlefield, Ariz., operated since 1947, shows that the stream contributes less than 3 percent as much sediment as is contributed by the Colorado River at Grand Canyon. Other tributaries also contribute some sediment to the reservoir. The record at Grand Canyon is of the suspended load only, and the sediment passing the station as bed load is unmeasured.

A comparison of the findings of the volumetric survey of 1948 with the record of suspended load at Grand Canyon shows that these ungaged increments must be small quantities, evidently smaller than the limits of error in the two systems of measuring the accumulated sediment. The suspended sediment measured at Grand Canyon from February 1, 1935, until the completion of the volumetric survey on February 28, 1949, totaled 1,990 million tons. Somewhat less than 10 million tons continued through the reservoir and on downstream prior to May 1936, leaving 1,980 million tons to accumulate in the Colorado delta in Lake Mead.

The total weight of sediment in Lake Mead, as calculated in the volumetric survey of 1948–49, was 2,014 million tons, of which about 57 million tons, or less than 3 percent, was deposited by the Virgin River in the upper part of the Overton Arm. Thus the sediment in the Colorado delta totaled only 1,957 million tons. However, this determination is based on differences between the topography as shown by maps made in 1935 and the bottom topography as determined in 1948–49. The surveys for the 1935 maps were not completed in some areas until sediment deposition had already begun, and it has been estimated (p. 168) that as much as 43 million tons may have been included in the "pre-Lake Mead" topography.

Also, the sediment as calculated from the volumetric survey may be less than the total deposited in the period February 1, 1935, to February 28, 1949, because of the continuing deposition of sediment throughout the period of the hydrographic survey. About 115 million tons of suspended sediment passed the Grand Canyon station during the year of the survey, of which 100 million tons was recorded in the first 5 months (March–July 1948, inclusive). These are the months of the annual freshet, when most of the suspended load is likely to be of sand size, and clay-sized particles commonly make up less than 10 percent of the total; practically all the sand and the coarser grades of silt are deposited in the eastern part of the lake, particularly in Lower Granite Gorge (p. 173). The surveys of these areas were begun after the freshet was over, and the measured sediment probably includes most of the 1948 increment. An unknown proportion of the 15 million tons of sediment carried by the river in the 7 months from August 1948 to February 1949 may have been

deposited subsequent to the completion of the hydrographic survey in some parts of the reservoir.

It is evident that if the total as calculated by the volumetric survey is adjusted because of uncertainties as to sedimentation at the beginning and end of the base period, it might be increased by as much as 60 million tons. Thus the total in the Colorado delta may well be stated as ranging from about 1,960 million to 2,020 million tons. The calculated suspended load at Grand Canyon is near the midpoint of this range, and there is thus no indication that the bed load at Grand Canyon or unengaged sediment from other sources constitutes a significant proportion of that delta.

VARIATIONS IN RATE OF SEDIMENT INFLOW
VARIATIONS IN SEDIMENT LOAD AND RUNOFF

The record of sediment at Grand Canyon, beginning in 1926, provides information as to the suspended load and contemporaneous runoff for a quarter of a century. Records of river discharge cover a longer period, and climatic fluctuations are inferred for a still longer period, but the sediment-runoff relations in these extended periods must be extrapolated from the relatively short sediment-gaging records.

The average annual load of suspended sediment passing the Grand Canyon gaging station in the 25-year period 1926-50 was 168 million tons (table 10), or about 18 percent greater than the mean annual load (142 million tons) during the 14-year period 1935-48. The mean annual runoff in the 25-year period was 12.8 million acre-feet, or 2 percent greater than the average for the period 1935-48.

Some further qualitative knowledge of the amount of sediment removed from the Upper Colorado River Basin during an earlier period may be obtained from the suspended-sediment records taken at Yuma, Ariz., from 1911 to 1934. The mean annual suspended load that passed Yuma between 1911 and 1925 was about 38 percent greater than in the period 1926-34. The total quantity of suspended sediment discharged at Yuma during any given year has always been smaller than that which passes the Grand Canyon station, as determined by comparison of the records at these stations during the period 1926-34; the annual sediment load recorded at Yuma varied between 36 percent and 78 percent of the annual suspended load recorded at the Grand Canyon station. Nevertheless, the sediment records at the two stations show the same general trend. Both high and low sediment loads at the Grand Canyon station are reflected by corresponding high and low values at Yuma, though there is no constant relation between the total quantity of sediment discharged at the two stations during any given year. Even though these records are not directly comparable, the high sediment loads recorded at Yuma from 1911 to 1925 suggest a greater rate of sediment movement by the Colorado River in those years than in the period 1926-50.

From this brief analysis of the historical suspended-sediment data, it appears that the average annual rate of sediment transport into the Lake Mead area during the 25-year period 1926-50 was about 18 percent greater than during the 14-year period 1935-48. If the high suspended load recorded at Yuma, Ariz., in the years 1911-25 is representative of the Upper Colorado River Basin, it appears that the rate of sediment transport into the Lake Mead area during the 40-year period 1911-50 may possibly be as much as 50 percent above the 1935-48 average.

Records of the discharge of the Colorado River have been obtained continuously since 1921 at Lees Ferry, Ariz., 87 miles upstream from the Grand Canyon station and just above the mouth of the Paria River. These records have been extended back to 1895 by estimates based on fragmentary records from downstream stations and from tributaries (U.S. Geol. Survey, 1954, p. 522). According to this record, the average annual discharge at Lees Ferry in the 56-year period 1895-1950 was 13.8 million acre-feet and in the 25-year period 1926-50 was 12.4 million acre-feet. Thus in the 56-year period the river discharge at Lees Ferry was about 12 percent greater than in the period 1925-50. It has been estimated that diversions for irrigation, reservoir evaporation, and exports of water from the basin upstream from Lees Ferry reduced the streamflow at that point by 0.7 million acre-feet in 1897. By 1921 these stream depletions had increased to 2.6 million acre-feet, and they have exceeded 2 million acre-feet in most years since 1926. Thus the lesser flow in the period 1926-50 is attributed only in part to natural climatologic changes, and partly to increased diversions from the river. The estimated virgin flow at Lees Ferry in the period 1895-1950 is 15.7 million acre-feet.

The tributary inflow between Lees Ferry and Grand Canyon is relatively small, and is derived chiefly from springs and from the Little Colorado River. In the period 1926-50 the average annual flow at Grand Canyon was 12.8 million acre-feet, or about 0.4 million acre-feet greater than at Lees Ferry. By analogy with Lees Ferry, it may be inferred that the mean annual discharge at Grand Canyon in the 56-year period 1895-1950 was about 12 percent greater than in the period 1926-50, or about 14.2 million acre-feet. Also by analogy with Lees Ferry, the estimated virgin flow at
Grand Canyon in the 56-year period is of the order of 16 million acre-feet.

La Rue (1928, p. 121, pl. 74) extended the stream-discharge record for Lees Ferry back to 1851, by means of correlation with the historic and traditional records of the level of Great Salt Lake. According to this extended record, the virgin runoff of the Colorado River at Lees Ferry in the 72-year period 1851–1922 averaged 16 million acre-feet a year. This estimate is based on more tenuous evidence than that for the 56-year period 1895–1950, but is of the same order of magnitude and suggests that the hydrologic records now available are sufficient to give a firm figure for long-term mean runoff.

By using Schulman’s results (1943) from tree-ring investigations in the Upper Colorado River Basin we can obtain an estimate of the average rate of runoff of the Colorado River during the past several hundred years. According to Schulman, there is general agreement among rainfall, runoff, and tree growth in the Upper Colorado River Basin during the period for which rainfall and runoff data are available. By tree-ring dating methods he has concluded that the growth index of the Douglas fir during the years 1887–1945 has varied considerably from the mean for the 68-year period 1288–1945. He reports (1945, p. 44) that this growth index in 1887–1905 was 18.1 percent less than the 68-year average, whereas during the interval 1906–30 it was 16.1 percent above the long-term average. From 1931 to 1940 the growth index was 19.7 percent below the average, but it was near normal during the interval 1941–45. Since there is general correspondence between the tree-growth index and runoff in 50 years of contemporaneous records, we can conclude that the runoff in past centuries also has probably experienced the same general fluctuations as the tree growth.

Extrapolation of these results, together with available runoff records, suggests that the average annual virgin streamflow (i.e., flow undepleted by artificial diversion for irrigation and other uses) at the Grand Canyon station during the past 658 years has been about 15.8 million acre-feet, which is slightly less than the estimated virgin flow in the 56 years—1895–1950. However, this long-term average is about 14 percent greater than the estimated actual flow in the 56 years, 24 percent greater than the measured flow in the period 1926–50, and 26 percent greater than the average discharge in the 14-year period 1935–48.

The depletions caused by water development in the Upper Basin, currently about 2.2 million acre-feet a year, will doubtless insure that the average flow at Grand Canyon in the future will be less than the average as derived from tree-ring records. With no increase in the amount of upstream diversions, this long-time future average should be about 13.8 million acre-feet, or about 10 percent greater than the average in the 14-year period 1935–48.

Variations in Relation to Sediment Runoff

In four years since 1926 the annual runoff at Grand Canyon was close to the projected long-term mean of 13.8 million acre-feet: In 1930, 1944, 1947, and 1948 the runoff ranged from 13.4 million to 13.9 million acre-feet. These four years demonstrate the striking variation in sediment transport that is all too characteristic of the records to date. The measured sediment load was more than 235 million tons in 1930, but less than 98 million tons in 1944. In both 1947 and 1948 the load was close to the 142-million-ton average for the 14-year period of 1935–48. These inconsistencies are apparent throughout the record, including years of high as well as low runoff. Thus in 1950 less sediment was carried in 11.2 million acre-feet of water than was transported by 6.7 million acre-feet in 1931; and 17.3 million acre-feet of water carried 389 million tons of sediment in 1927, but only 230 million tons in 1942.

The monthly sediment load at Grand Canyon has ranged from 156,000 tons in January 1944 to 134 million tons in August 1929. This variation is far more striking than is the variation in annual load, for the maximum monthly load is about 85 times the minimum, and is nearly as large as the average annual load since 1935. Graphs of monthly sediment load and average discharge at Grand Canyon since the completion of Hoover Dam are presented in figure 62, which shows a maximum in sediment load each year corresponding to the peak discharges of May and June. In almost every year there is also a secondary maximum (shown by ruled pattern) usually in August or September but sometimes as late as October; in 1936, 1940, 1946, and 1947 these later sediment-load maxima were greater than those in the spring. The river discharge during the months of these secondary maxima is much less during May and June. The average percentage of sediment by weight also rises to a maximum in May and June, and to a second maximum in the late summer or autumn (shaded in figure 62), but the second maximum is generally higher than the first. In other words, the high sediment loads in the late summer and fall generally occur with higher concentrations of sediment than those in the spring. The months of November to February are generally months of minimum flow, minimum sediment load, and minimum concentration of sediment.
A logarithmic plot of monthly runoff against sediment load (fig. 63) shows the following relations:

1. Points representing months when runoff was less than 1 million acre-feet and sediment load less than 5 million tons form a fairly straight and well-defined band. Generally these are the months November to February. Points representing the months of March and of August to October are more widely dispersed, but most of them also fall in the straight band noted above, or in its extension.

2. Points shown by open circles, which represent the months of maximum discharge (April–July), are generally above the band defined by paragraph 1, and form a band with different slope. Thus the sediment load is less during the annual freshet than is to be expected from the sediment–runoff relation as defined in other months of the year. After the peak discharge, notably in July, the river generally carries less sediment than it did with equivalent discharge during rising stage in April or May, and it transports only about as much sediment as it had carried with far less water in March or April.

3. Several points are below the band defined by the points mentioned in paragraph 1. All but five of these points represent months in the years 1931, 1933, 1934, 1935, 1939, 1940, and 1946, the 7 years of least runoff in the period of record, and months in those years are depicted by larger circles on figure 63. Many points within the lower part of the band also represent months in those dry years. In the months of greatest runoff during those dry years (April to July, shown by double open circles), the sediment load was commonly greater in proportion to runoff than in corresponding months of other years. Generally in these dry years the sediment load was greater than it is to be expected from the sediment–runoff relation suggested by the points mentioned in paragraphs 1 and 2.

The band in which the majority of points are located (par. 1) appears to be an expression of the fundamental relation of runoff to sediment load, when the sediment is predominantly clay and silt: The load is a power function of discharge. This relation involves the interaction of several variables, including all velocities expressible in terms of discharge. Because of this relation, the sediment load can be expected to increase with, but at a rate faster than, the runoff—an increase that is apparent in annual relations. However, the divergences of many points from this general relation indicate that other factors are involved, and these factors may be such as to render valueless any projections into the future of the short period of available record.

The band formed by the points representing the months of greatest runoff (par. 2) indicates that there is a different power relation when the suspended load includes a higher proportion of fine and medium sand (125 to 500 microns in diameter). As pointed out by Leopold and Maddock (1953, p. 40), in discussing experiments with such sands, "With increasing discharge the bed may change successively through conditions described as smooth, ripples, bars, dunes, and
finally antidunes." Such changes in bed configuration may change the channel roughness significantly. As summarized by Leopold and Maddock, "An increase in bed roughness is one type of change that will result in the decrease of velocity with respect to depth. Because changes in the velocity-depth relation constitute a part of the adjustment of channel shape to load, variations in roughness affect capacity for load."

During periods of drought the suspended load may be substantially greater than would be expected by the usual power relations. This may be a reflection of the broad interrelations among climatology, vegetative cover, runoff, and erosion in the tributary drainage basin, and forecasts of sediment load may be considerably in error if they neglect these factors. Daines (1949), following his analysis of sediment load in relation to runoff and precipitation, concludes that:

Intensity, duration, frequency, distribution, and season of occurrence of precipitation—not total amount—effects variations in the runoff-sediment discharge relation. Occasional intense storms may flush away considerable sediment loads, while other storms of equal volume may have very little erosive effect depending upon rainfall characteristics and ground conditions. Correlation of sediment discharge with all of the rainfall characteristics would undoubtedly give better results than correlation with runoff alone; however, inadequate information precludes the possibility of direct correlation of sediment with all rainfall characteristics.

Analysis of the record by months suggests that there may be possibilities of isolating the factors which contribute to the complexity of the sediment-runoff relation. Quantitative evaluation of the effects of individual factors will require more detailed analysis, using smaller time units as well as smaller geographic units, such as records for individual storms and for gaging stations that can segregate the sources of the sediment load.

As shown by figure 22, the sediment-runoff relation in the years 1942 to 1950 is as consistent as for earlier years of record, and the curve showing that relation is approximately parallel to that drawn on the basis of records for the years 1926 to 1940. However, in each of the later nine years the annual sediment load was 50 million to 100 million tons less than would be expected on the basis of the curve established by data for years prior to 1941.

The analysis of monthly records indicates a greater amount of sediment in dry years than would be expected from the usual sediment-runoff relations, and
it is noted that the period 1942–50 includes only one (1946) of the seven years of least runoff since 1926; the other six occurred in the decade 1931–40. The analysis of monthly records also shows that during the annual freshet (generally April–July) the sediment load is commonly less than is to be expected from the relation that characterizes other months. There is no indication, however, that the annual freshets in recent years carry a significantly larger proportion of the yearly runoff than in earlier years. The April–July runoff has constituted 65 to 75 percent of the annual total in all except six of the years since 1926; those six exceptional years (1930, 1951, 1934, 1939, 1940, and 1946) have been years generally of minimum annual runoff, and the April–July runoff has been as little as 50 percent of the total for the year.

In general, neither the annual runoff nor the seasonal distribution of runoff since 1941 has been perceptibly different from that in earlier years, and thus neither offers an explanation for the change in sediment-runoff relations since that year. Because 1941 introduced a new and different relation that has persisted for at least 9 years, the factor or factors causing the change must have been effective for a similarly long period. It is believed that a possible explanation may lie in long-term regional trends in precipitation.

The southwestern United States in recent years has recorded a drought which is recognized as one of the eight most severe droughts in 600 years. This drought began in 1942 in Arizona and southern Utah, 1943 in New Mexico and west Texas, and 1945 in California; as of October 1951 it had not yet ended (U.S. Dept. Interior, 1951). Lake Mead is within this broad drought region, but the principal sources of its water supply are far to the north, in a region where precipitation has generally been about normal.

Records of annual statewide precipitation in percent of normal, as published by the Weather Bureau (1952), give some indication of regional variations in precipitation trends, although the averages for the Colorado River basin States are based in part on records from areas beyond the limits of the basin. These averages indicate that precipitation was approximately normal throughout the Colorado River basin and a broad surrounding area in the years 1935 to 1938; it was somewhat below normal in 1939, and near normal again in 1940. The following year, 1941, was a banner year for precipitation in a broad region that included the entire Colorado River basin. During the first 7 years of Lake Mead history the precipitation trends were fairly similar throughout the basin.

By contrast, the years since 1941 have been characterized by marked variations in different parts of the basin. In 1942 the average precipitation in Arizona was less than 70 percent of normal, but precipitation in other States of the basin was approximately normal. From 1943 through 1948 there was a notable contrast between precipitation in Arizona and New Mexico and the States farther north. Thus in Colorado, Wyoming, and Utah precipitation was appreciably above normal in 1944, 1945, 1946, and 1947, and only slightly below average in 1943 and 1948. In drought-ridden Arizona and New Mexico (and bordering areas in southern California, Nevada, Utah, and Colorado) precipitation was generally less than 85 percent of normal in 1943, 1945, 1947, and 1948, and slightly below normal in 1944 and 1946.

These contrasting precipitation patterns are of significance in the consideration of sediment-runoff relations, because the drought-affected area included most of the sediment-producing area of the Colorado River basin. Precipitation was less than 85 percent of normal in 6 or more of the 9 years 1942–50 in the basins of the Virgin, Little Colorado, San Juan, and Dirty Devil Rivers and of smaller tributaries that enter Colorado River below the mouth of Green River. In 3 to 5 of those years similar drought conditions prevailed in the basins of the Price, Duchesne, and Dolores Rivers. However, the basins of the major water-producing tributaries—the Green, Yampa, Colorado, and Gunnison Rivers—received approximately normal precipitation throughout the 9 years.

The change in the annual sediment-runoff relation since 1941 may well be a product of drought: reduced streamflows in sediment-producing tributaries and corresponding reduction in contribution of sediment from them, in association with normal streamflow from the high headwater areas in Colorado, Wyoming, and northern Utah.

This explanation—that drought may cause sediment loads smaller than expected by the usual sediment-runoff relations—appears to conflict with the conclusion on page 237 that the sediment loads are greater than normal in drought years. It is evident that the evaluation of the effects of drought cannot be made from general information for the entire basin, but must have specific data on the subdivisions of that basin.

VARIATIONS RESULTING FROM WATER DEVELOPMENT

The existing developments of water in the drainage basin tributary to Lake Mead consist of diversions from the main stem above Grand Junction, Colo., and from tributaries. The natural distribution of flow of the river is essentially unmodified by these developments, for the aggregate storage capacity of existing reservoirs serving the Colorado River basin above Grand Canyon is less than 1 million acre-feet.
These developments deplete the flow of the Colorado River at Grand Canyon by an amount estimated at more than 2 million acre-feet annually. The effect of this depletion upon the transportation of sediment through Grand Canyon is not known to the writers. Obviously the diverted water cannot transport sediment through the canyon, but that water may have been involved in erosion and sediment transportation prior to its diversion from the river, and thus may have had an indirect influence upon the sediment load at Grand Canyon.

Full development of the water resources of the Colorado River basin will require several large dams upstream from Hoover Dam (U.S. Bur. Reclamation, 1946, 1950). Two of the proposed dams would be on the main stem. The Bridge Canyon dam would be 120 miles upstream from Hoover Dam, in Lower Granite Gorge just above the high-water level of Lake Mead; with a height of about 700 feet, it would form a reservoir with 3.7 million acre-feet capacity. The proposed Glen Canyon dam would be 370 miles upstream from Hoover Dam, and would rise 580 feet above the present river bed; its capacity would be about 26 million acre-feet.

The proposed Bridge Canyon reservoir would intercept all the sediment flowing past the Grand Canyon gaging station and thus would reduce the sediment in-flow to Lake Mead to the small quantities contributed by the Virgin River and ephemeral tributaries to the lake—a contribution that currently amounts to less than 5 percent of the total. However, the capacity of Bridge Canyon is so small that it could assume this sediment burden for only a relatively short time: its water-storage capacity is about 12 percent of that of Lake Mead, and if sediment storage and compaction in the two reservoirs are proportional, the Bridge Canyon reservoir would take about 12 billion tons for complete filling, or about 6 times as much sediment as was carried into Lake Mead in a 14-year period. To prolong the useful life of this reservoir, current plans envisage the construction of the Bridge Canyon dam after sediment-storage facilities have been provided in Glen Canyon.

The sediment-storage capacity of Lake Mead might be reduced slightly by operation of the Bridge Canyon dam, which is planned at mile 237 below Lees Ferry. It has been predicted (p. 216) that as sediment accumulates in Lake Mead the head of the Colorado delta will migrate upstream, and will be at mile 221.5 (15 miles above the Bridge Canyon dam site) when the lake is completely filled with sediment. Experience at Hoover Dam and at Parker Dam (Stanley, 1951) shows that clear water released from a dam is likely to erode the channel below the dam and carry sediment downstream. Thus some of the sediment that would be deposited above the Hoover Dam spillway level might be washed down into Lake Mead by releases from the Bridge Canyon dam.

The proposed Glen Canyon reservoir also would intercept all the sediment that now moves toward Lake Mead, except for the quantities contributed by the Virgin and Little Colorado Rivers, and minor tributaries that contribute very little water but are likely to have high concentrations of sediment when they do flow. The record from the Lees Ferry gaging station indicates the suspended load that would be intercepted by the Glen Canyon dam 15 miles upstream; but there are no data for estimating the bedload that passes the station. In 6 years of contemporaneous records, the suspended load at Lees Ferry averaged 80 percent of that measured at Grand Canyon.

The proposed Glen Canyon reservoir (U.S. Bur. Reclamation, 1950) is comparable in magnitude with Lake Mead. It will have about 90 percent of the water-storage capacity upon completion, and its maximum water depth and water-surface area will be almost as great as those of Lake Mead. Inactive storage in Glen Canyon (that is, storage space below the level of the lowest outlet) will be almost twice that in Lake Mead. Its probable sediment-storage capacity has not been calculated on the basis of the findings of the Lake Mead survey but is presumed also to be similar to that of Lake Mead.

Obviously the construction of Glen Canyon dam, and the interception of more than 75 percent of the sediment load that now moves into Lake Mead, would prolong the life of Lake Mead by several centuries. Lake Mead would necessarily outlive the Glen Canyon reservoir unless the Glen Canyon dam were constructed and operated so as to pass large quantities of sediment downstream. With both reservoirs in operation, any estimate of the life of each would require collection and analysis of additional data.

In addition to the Glen Canyon dam, nine other dams have been proposed in the Colorado River storage project (U.S. Bur. Reclamation, 1950). These are all upstream from the area that yields the bulk of the sediment to the Colorado River, and according to the preliminary estimates made for the Colorado River storage project, all of them combined would intercept only about one-fourth as much sediment as Glen Canyon. So far as interception of sediment is concerned, these reservoirs will add little to the life of Glen Canyon reservoir or Lake Mead.

There remains the question as to the effect of regulation and use of water within the Upper Basin, which is the prime purpose of the Colorado River storage project. By the terms of Article III of the Colorado...
River Compact, the Lower Basin was given the right to exclusive beneficial use of waters of the Colorado River system amounting to 7.5 million acre-feet per annum, plus the right to increase its beneficial use of such waters by 1 million acre-feet per annum. The treaty with the United States of Mexico requires deliveries across the international border of 1.5 million acre-feet of water, from surplus if available, but otherwise to be supplied equally from waters previously allocated respectively to the Upper and Lower Basins. Thus the average annual deliveries to the Lower Basin as computed for the compact point at Lee Ferry may be reduced ultimately to 7.5 million plus 1 million plus 0.75 million acre-feet, a total of 9.25 million acre-feet. Compared with average annual flows of 12.4 million acre-feet at Lee Ferry in 1935–48, this is a reduction of about 25 percent.

In evaluating the effect of these upstream reservoirs and subsequent development and use of water in the Upper Basin upon sediment accumulation in Glen Canyon and Lake Mead, the following points should be noted: (1) The reduction in annual runoff will cause some reduction in sediment transportation, according to the sediment-runoff relations that have been observed. (2) Regulation by upstream reservoirs will probably insure more uniform distribution of runoff throughout the year. Because of reduction in April–July peak flows, the quantities of coarser (sand-size) particles in the suspended load in those months will probably be reduced. (3) With regulation, the minimum (August–March) flows may be no less than those recorded in the past, and may be substantially greater, even though the annual runoff is reduced 25 percent. Thus the river will be capable of carrying high concentrations and high total loads of silt and clay-sized particles in some periods. (4) If the proposed Coconino and Navajo dams are constructed on the Little Colorado and San Juan Rivers, respectively, they will intercept a considerable proportion of the sediment coming from the Four Corners area; otherwise the tributaries draining that region will continue to carry large sediment loads into the main stem.

**VARIATIONS IN RATE OF SEDIMENT OUTFLOW**

The life of Lake Mead will be prolonged if some of the sediment is permitted to pass through the reservoir and dam and continue downstream. At the present time, of course, there is no possibility of passing sediment through the intake towers, and there is little likelihood of doing so in the near future because the water is usually clear at the lower gates of the intake towers.

The sediment surface at the dam rose to its highest recorded level in 1941, and was then 130 feet below the sills of the lower gates of the intake towers. In the following decade the recorded sediment level ranged from 140 to 175 feet below those sills (fig. 24). At some time in the future it is inevitable that the sediment surface will approach the sills, and it will then become a question of operational policy whether to cease using the lowest reservoir outlets or to draw sediment-laden water through them. It was stated (p. 226) that passage of silt and clay through the turbines will not cause undue mechanical trouble.

As estimated on page 224, the sediment surface at the intake towers will rise to the sills of the lower gates when the total weight of sediment accumulation reaches 13.5 billion tons. This is about 7 times as much as accumulated in 1935–48, and if the rate of accumulation does not change, almost a century will be required for its accumulation.

Even if passage of sediment-laden water through the lower gates is accepted as normal procedure, the outflow of sediment will be nil for several decades, while the sediment surface rises toward the 805-foot level. Then one can expect sediment outflow, occasionally at first as a result of exceptional turbidity currents, then more frequently and with greater volumes of sediment as the sediment surface in Boulder Basin continues to rise. Ultimately the sediment surface may develop a slope which would permit a large fraction of the finer materials to flow out of the reservoir.

The problem of sediment outflow through the upper gates at 1,045 feet elevation is analogous; but it is conditioned upon the closing of the lower gates when the sediment surface approaches them, so that sediment continues to accumulate near the dam. As pointed out on page 223, the sediment surface may still be slightly below the sills of the upper gates at the halfway point when the weight of the accumulated sediment becomes 18 times as great as the quantity deposited from 1935–48, even with no sediment outflow from the reservoir.

**PROBABLE RATES OF SEDIMENT ACCUMULATION IN THE FUTURE**

From the foregoing discussion, the following conclusions are believed to be warranted as to the future rates of sediment accumulation in Lake Mead:

1. The average annual rate of suspended-load transport at Grand Canyon in the 14-year period 1935–48 was 142 million tons, and this rate is well confirmed by the calculated total of sediment accumulated in Lake Mead during the period. However, the quantities calculated by both methods are probably 3 to 5 percent less than the total sediment deposited in the lake in the 14-year period. The error in suspended-load measurements results chiefly from the omission of unmeasured
loads of the Virgin River and other minor tributaries to the lake, whereas the error in measurement of the quantity of sediment accumulated in the lake results from the omission of unmeasured amounts of sediment deposited during the 1935 and 1948 surveys. The uppermost graph of figure 64 is based on the assumption that sediment accumulation will continue at the rate of about 148 million tons a year, or 4 percent more than the average annual suspended load at Grand Canyon during 1935–48.

2. The average annual rate of suspended-load transport at Grand Canyon in the last 7 years of this 14-year period was only 104 million tons per year, but this reduced rate is attributed to exceptional climatic variations within the basin and is not considered to be indicative of future trends. Inclusion of the data for these 7 years has of course lowered the average annual rate in the 14-year period.

3. The average annual suspended-load transport at Grand Canyon in the 25-year period 1926–50 was 168 million tons, and if a 4-percent allowance is made for unmeasured contributions to the river above Black Canyon (as in 1935–48) the estimated average rate of sediment inflow to the Lake Mead area would be increased to 175 million tons a year. Most of the graphs of figure 64 are based on a projection of this rate.

4. Correlation of sediment records at Grand Canyon and at Yuma is considered to be too weak to justify conclusions as to rates in years prior to 1926.

5. The average annual runoff in the 25-year period 1926–50 was only 2 percent greater than in the 14-year period 1935–48. There is evidence from tree-ring studies that the long-term average virgin flow of the Colorado River at Grand Canyon is of the order of 15.8 million acre-feet annually, which is slightly less than the average obtained from extended records of streamflow in 1895–1950, corrected for stream depletions. With current depletions, however, the estimated long-term average at Grand Canyon is about 13.6 million acre-feet a year. The 1926-40 curve on figure 22 offers a possible sediment-runoff relation, based on 15 years of record: with average annual runoff of 13.6 million acre-feet the average annual sediment load would be of the order of 200 million tons, which, when increased 5 percent for other sources of sediment, gives a long-term average sediment inflow of 210 million tons. The basis for this estimate is weak, because of the great uncertainty as to the sediment-runoff relation.

6. The Glen Canyon reservoir, if constructed, will intercept more than 75 percent of the sediment moving toward Lake Mead; together with Bridge Canyon reservoir it will intercept about 93 percent of it, until the two reservoirs start spilling sediment. Upstream development and use of water may reduce the sediment inflow to these two reservoirs by about 25 percent.

7. After the sediment level at Hoover Dam has risen to the level of the lower outlet gates, silt and clay can be passed through the turbines until the rate of sediment outflow approaches one-half the rate of sediment inflow.

The graphs of figure 64 demonstrate the variation in estimates that have been based on various assumptions as to the future. More significantly, they show that the benefits of Lake Mead will be felt for centuries to come, and that the usefulness of the reservoir will not be seriously impaired for as long a time as is predictable in this day of rapidly advancing science.

**MISCELLANEOUS CHANGES IN RESERVOIR VOLUME**

In the preceding chapters, numerous minor changes since 1935 in the configuration of the bed and banks of Lake Mead have been discussed. Some of these modifications have caused increases or decreases in the water-storage volume at certain reservoir levels without changing the over-all storage capacity—for example, the erosion of some parts of the reservoir floor and redeposition elsewhere within the reservoir (p. 209), and the slumping of walls below the high-water line (p. 209). Other modifications have changed the over-all storage capacity, as for example the downwarping of the earth’s crust (p. 37), the compaction of loose materials forming the original floor of the reservoir (p. 36), and the dissolving of gypsum and rock salt (halite, sylvite, and other mineral salts) (p. 212). In comparison with the major changes in water-storage volume caused by sediment accumulation, all other changes to date have been insignificant (p. 70–71).

**DOWNWARPING OF THE RESERVOIR FLOOR**

The weight of water in Lake Mead caused enough downwarping to be measurable in 1941, when the lake held about 85 percent of its capacity. The downwarping was greatest in the crustal blocks adjacent to the Boulder and Virgin Basins but amounted at most to only a few inches, and it was concluded that the resulting net changes in reservoir volume were very small (p. 38).

As the reservoir fills with sediment, the total load upon the earth’s crust will increase to almost twice the load that resulted from filling the lake to capacity with water. However, any change in reservoir volume will depend upon the differential settlement of the reservoir floor with respect to the dam, and upon the effect of differential crustal movements independent of the reservoir.
COMPREHENSIVE SURVEY OF SEDIMENTATION IN LAKE MEAD, 1948-49

1. Assuming no sediment outflow; no development upstream

2. Assuming no sediment outflow; no development upstream

3. Assuming no sediment outflow; no development upstream

4. Assuming sediment outflow will begin after first century and increase to 80 million tons annually

5. Assuming Glen Canyon reservoir intercepts 75 percent of sediment until it is filled

6. Assuming Glen Canyon and Bridge Canyon reservoirs intercept 95 percent of sediment until they are filled

7. Assuming same as 6, and also that upstream reservoirs reduce sediment inflow to Glen Canyon by 25 percent

YEAR

1935 2000 2100 2200 2300 2400 2500 2600

EXPLANATION
Width of bar is proportional to net rate of sediment accumulation

Indicates time when water-storage capacity is reduced to 13 million acre-feet

FIGURE 64.—Actuarial projections for Lake Mead, showing estimated dates when it will be completely filled with sediment.
Most of the reservoir, particularly the broad basins, is underlain by unconsolidated clay, silt, sand, and gravel. The details of the composition and thickness of these materials are unknown, and no surmises have been made as to the compaction that may result from the burden of water or of sediment in the reservoir. The methods used in the 1948 hydrographic survey were such as to measure the net change in water-storage volume since 1935. Thus consideration of any compaction of underlying unconsolidated materials, if measurable, would result in a lesser computed volume of sediment than the actual total.

**DISSOLVING OF MATERIALS OF THE RESERVOIR FLOOR**

About 20 million tons of material, chiefly gypsum and some halite, was dissolved from the reservoir bed and banks by the lake water in the period 1935–48, and it was estimated that this solution increased the volume of the reservoir by about 6,100 acre-feet (p. 213). It might be expected, however, that the rate of solution would be greatest in the early years of reservoir history, when the soluble outcrops are most accessible to the lake water, and would decrease progressively as solution progresses farther into the soluble rock, or as those rocks are covered and protected by sediment, and other inorganic and organic material.

The records of dissolved solids in the inflowing and outflowing water give some indication as to the relative rates of solution since 1935. The weighted average salinity of the water at Grand Canyon is shown graphically in figure 65 for each year, beginning with 1935. Another graph shows the 3-year progressive average salinity—that is, each point represents the average of the preceding 3 years—on the premise that the reservoir is large enough to store and mix the water from as much as three years of inflow. The trend of this 3-year progressive average is similar to the trend in weighted average salinity of the outflow, also shown in figure 65, except in 1941 when the inflow amounted to about two-thirds of the reservoir capacity. From 1937 to 1943 the average salinity of the outflow was 15 to 25 percent greater than the 3-year average.

**Figure 65.**—Weighted average salinity of inflowing and outflowing water of Lake Mead since 1935.
salinity of the inflow, but it has been only 7 to 9 percent greater in each year since 1946.

So far as can be discerned from these data alone, it thus appears that the rate of solution of gypsum was greatest in the first decade of reservoir history. Since 1946 the salinity of the outflowing water has been somewhat greater than the 3-year average of the inflow, but that increase can be accounted for largely by evaporation and by unmeasured inflow to the reservoir. Thus the prospects for even a slight increase in reservoir volume by such dissolving action in the future are not bright. However, the quality of the outflowing water in the future should be only slightly inferior to the 3-year average inflow, and it is possible that the salinity of the annual outflow will not again exceed about 700 ppm until and unless there is a significant and sustained increase in dissolved solids in the inflowing water.

REFERENCES CITED


